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HYDRAULIC STUDIES OF A VERTICAL SHAFT INTAKE TO A PRESSURE TUNNEL

by

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James W. Ball[1] and Jack C. Schuster[2]

SUMMARY

The hydraulic studies discussed in this paper were made for the purpose of determining the most suitable design of vertical intake shaft for conveying water from a small diversion reservoir to a pressure tunnel 300 feet below the ground surface. Three shaft designs were considered: (1) one in which the water entered through a morning-glory shaped entrance and plunged into the partly full shaft, (2) one in which the jet from a control at the top of the shaft plunged through a vacuum in the upper portion of the shaft into the partly full shaft, and (3) one in which the shaft was kept under pressure by a control at the bottom of the shaft so that air would not enter. The considerations and model tests which concerned each design and led to the final hydraulic features of the third and adopted design are discussed.

INTRODUCTION

The Eucumbene-Tumut Tunnel is located in the Snowy Mountains area of southeastern Australia near Cooma about 260 miles southwest of Sydney (Figure 1). The 21-foot-diameter tunnel connects the large Adaminaby storage reservoir on the Eucumbene River to the power reservoir (Tumut Pond) on the Tumut River about 14 miles through the mountain range. An 18-foot-diameter vertical shaft intersects the tunnel about 10-1/2 miles from the portal at Adaminaby Reservoir (Figure 2). This shaft receives water from a small diversion reservoir (Junction Pond) at the confluence of the Tumut and Happy Jacks rivers and discharges it into the tunnel about 300 feet below the ground surface; the tunnel conveys the water to Adaminaby Reservoir when the combined flows of the rivers exceed the capacity of the powerplant at Tumut Pond. The water thus stored later flows through the tunnel to Tumut Pond when the flows from the Tumut and Happy Jacks rivers are insufficient to supply the demands at Tumut Pond. The design of this shaft to divert water quantities up to 9,000 cfs from Junction Pond to Adaminaby Reservoir was evolved through the aid of comprehensive hydraulic model studies.

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The crest of the diversion dam at Junction Pond is elevation 3910 and the maximum flood level is elevation 3940. The crest of the morning-glory-type inlet structure, hexagonally shaped in plan, is at elevation 3885, 25 feet below the diversion dam crest (Figures 2 and 3). The inlet water passage is tapered downward from hexagonal at the crest to the 18-foot circular shaft in a 25-foot vertical distance. Piers at the corners of the hexagon support a hexagonally shaped enclosure of concrete extending upward to elevation 3940. This enclosure supports the trashracks, cylinder gate hoist equipment, and the bulkhead gates for unwatering the shaft.

The 18-foot-inside-diameter shaft connects the inlet structure to an enlarged section in the 21-foot-diameter Eucumbene-Tumut Tunnel.

THE PROBLEM

The problem was to develop by model studies a hydraulically sound design of vertical intake shaft for conveying floodwaters from Junction Pond to the Eucumbene-Tumut Tunnel.

Six models (including an aerodynamic model and an electric analog) were used in solving the hydraulic design problems pertaining to this tunnel intake system. Two of these models were used to establish the inlet design. The others, including the aerodynamic model and the electric analog, were used to study the 20-foot 4-inch-diameter cylinder gate control which is to be in the base of the shaft.

INVESTIGATION OF VERTICAL SHAFT TUNNEL INTAKE

Types of Inlets Considered

Three types of inlets to the tunnel intake were considered: (1) one in which the water entered a morning-glory type of spillway entrance with free flow over the inlet crest, (2) one in which the discharge from a control at the top of the shaft plunged through a vacuum into the water-filled lower portion of the shaft, and (3) one in which the inlet was kept submerged to prevent air entrainment by regulating the amount of flow released from the bottom of the shaft into the tunnel.

Free Flow Inlet

Description of model. A 1:21.6 scale hydraulic model was used for the tests on the first and third types of inlets (Figure 4). The model represented a portion of Junction Pond, the inlet structure, and part of the 18-foot-diameter vertical shaft. The portion of the vertical shaft was represented by a 10-inch-inside-diameter transparent plastic pipe. Topography affecting the flow to the inlet structure was represented accurately by a cement-sand mortar placed over a framework of wire lath and wood. The flow approaching the inlet structure was passed through rock baffles to represent flow from the Tumut and Happy Jacks river channels.

Flow condition in model shaft. When the model was first operated as a morning-glory type spillway with the flow plunging over the crest and into the partially filled shaft, large quantities of air were entrained and much turbulence and surging were observed (Figures 5, 6, and 7).

Also, the nappe of water was alternately in contact and free from the interior surface of the inlet crest section. This unstable flow action occurred for nearly all discharges to the maximum of 9,000 cfs (Figure 5). The changing flow conditions of one or more nappes could cause undesirable vibration in the structure. This type of inlet structure was not considered suitable for free-flow operation. Even with the inlet designed to eliminate this action, large quantities of entrained air would be expected in the prototype junction shaft if it were operated under free-flow conditions. It was felt that such quantities of entrained air would induce violent surging with possible damaging effects when the air under substantial pressure was released in the tunnel control gate shaft or in the tunnel portal area at Adaminaby Reservoir. Such conditions were noted at the gate valve in the horizontal section of the model discharge pipe when the model was operated to represent the free-flow condition. The forces accompanying such air release could not be predicted from the small scale models and the limited information from available literature indicated adverse conditions would result if the free-discharge inlet were used. Accordingly, the free-discharge inlet was abandoned.

Controlled Inlet

Description of model. Another plan for regulating the flow of water from Junction Pond to the Eucumbene-Tumut Tunnel was to provide a control at the shaft inlet where it could be easily inspected or repaired. This control would exclude air from the shaft and the water would fall in the shaft where ejector action had created a vacuum equal to water vapor pressure.

A schematic model of the proposed control was constructed to demonstrate the characteristics of such a design (Figure 8). A 6-inch-inside-diameter pipe 18.5 feet long attached to the downstream side of an orifice plate represented the vertical shaft. A 1-1/2-inch sharp-edged orifice represented the control at the top of the shaft.

It was thought that cavitation might result from entrained vapor cavities when a high velocity jet plunged through a vacuum into a pool. Such a condition, of course, could not be studied on a small scale model because the action was dependent upon high velocity flow. It was believed that this condition could be demonstrated by discharging a small diameter jet at prototype velocity through a vacuum into a pool. The schematic model shown on Figure 8 was constructed for this purpose.

Model operation. It was estimated that the jet from the prototype control would have a maximum velocity of about 110 feet per second by the time it reached the water surface in the shaft. Therefore, a jet of water having a velocity of approximately 110 feet per second was discharged from the orifice down the pipe. The pipe flowed full unless the turbine pump on the discharge end was operated. The water level could be adjusted throughout the length of the 6-inch pipe by controlling the discharge from the 8-inch turbine pump. A pressure of 9 inches of water, absolute, surrounding the jet could be obtained by pumping the water from the 6-inch pipe.

Flow characteristics. The jet of water had the same appearance as one discharged into atmospheric pressure and had a measured divergence rate of about 1:50. Irregular surface eruptions were made visible with high-speed photography (Figure 9). These surface eruptions were presumably caused by turbulent eddies originating in the pipe system upstream of the orifice and not by the vacuum surrounding the jet. No attempt was made to reduce the turbulence because a jet with an irregular surface is likely to occur in any large control of this type.

Cavitation tests. The characteristic noise of cavitation was heard in the 6-inch pipe in the region where the jet penetrated the water. A section of plastic pipe, approximately 4-1/4 feet in length, was placed in this region to facilitate observation of the flow action. The flow in this pipe appeared to be a very turbulent mixture of water and vapor cavities. High-speed motion pictures through the plastic pipe disclosed a turbulent mixture, but separate cavities were not distinguishable. The vapor cavities seemed to be entrained in the turbulent flow with no definite concentration of collapse taking place. The maximum noise seemed centered 2 or 3 diameters downstream of the jet and water junction. A 2-foot length of 6-inch-inside-diameter, concrete-lined pipe was placed 12 feet below the orifice and the jet-water junction was maintained near the upper end of this pipe section to test for cavitation erosion (Figure 8).

A rapid erosion of the concrete lining by cavitation was expected because of the relatively high noise level. After 25 hours of operation with a jet velocity of 110 feet per second and a pressure of 9 inches of water absolute in the upper end of the pipe just below the orifice, no damage definitely attributable to cavitation could be detected (Figure 10A). Before replacing the pipe for additional testing, four areas chosen at random, two at each end, 90° apart, and 2 inches from the pipe ends, were photographed through a microscope at 12 times magnification. The 2-inch distance was limited by the photographic equipment. Photomicrographs of the same areas were again taken after 75 hours additional testing (total of 100 hours) because no increase in damage to the surface was evident to the naked eye. The photographs disclosed a change in the surface texture near the top of the pipe where the cavitation seemed concentrated (Figure 10B). Small holes in the concrete at 25 hours were enlarged after 75 hours more testing. Small amounts of the sand-cement mortar were removed and the texture of the surface seemed to have a spongy appearance, characteristic of cavitation erosion. The concrete surface 2 inches from the bottom of the pipe was essentially unchanged. Although no erosion of a large magnitude occurred, the characteristic noise of cavitation in the model and the slight erosion of the concrete surface in the region of cavitation concentration led to the conclusion that this type control was not suitable for the junction shaft of the Eucumbene-Tumut Tunnel.

An enlargement of the shaft to cause the cavity collapse to take place in the flow away from the shaft surfaces might make this type of control suitable for an installation where the shaft water level is relatively constant. Such an enlargement was not feasible for the junction shaft since the water level will vary almost the full height of the shaft.

Submerged Inlet (Adopted Design)

Flow conditions. Operation of the 1:21.6 scale model, with the inlet submerged prevented air entrainment. The submergence was accomplished by controlling the flow through the structure using the gate valve located in the discharge pipe. Flow conditions were tranquil with this method of operation which represented a control placed in the base of the shaft or in the tunnel.

As a result of these observations and discussions with the designers, it was decided that the investigation should be continued to determine (1) the feasibility of this operating method, (2) the minimum shaft water level with respect to the pond level that would prevent air entrainment with free flow at the crest, and (3) the head loss through the submerged bulkhead gate openings.

The minimum water level in the shaft with respect to the pond water level to prevent air entrainment is uncertain because air quantities entrained in model flow do not represent the larger quantities that are present in prototype flow. Dissimilarity in the degree of turbulence in the model and prototype at the interface of the air and water within the shaft is the principal reason for this difference.

An approximate maximum difference of 1-foot prototype from pond level to shaft level without air entrainment was indicated by the 1:21.6 scale model for discharges from 1,000 to 9,000 cfs with free flow over crest. Air entrainment is likely to occur at a smaller differential in the prototype because of the more turbulent flow.

Although flow conditions were tranquil in the inlet and pond for submerged operation, a slight surging and surface roughness occurred within the shaft (Figures 11 and 12). Flow conditions in the inlet were satisfactory at all flows when sufficient submergence was maintained. The submergence was sufficient for discharges up to 3,000 cfs when the pond was at elevation 3895. Ample submergence for discharges from 3,000 to 9,000 cfs was obtained when the pond elevation was raised from elevation 3895 to elevation 3910 in direct proportion to the discharge.

The operating mechanism of any control gate would have to be related to the pond level and the shaft water level to give the required submergence of the inlet. The difference between the pond and shaft water levels or the loss of head across the bulkhead gate opening was obtained for discharges up to 9,000 cfs. The head loss curve for the bulkhead gate openings submerged the equivalent of 1 foot (pond level 3895) at 3,000 cfs and 16 feet (pond level 3910, crest of diversion dam) at 9,000 cfs, Figure 13, was obtained for use in designing the cylinder gate controls.

Because the preliminary design inlet performed very satisfactorily when it was operated submerged, the design was adopted. All subsequent tests were focused toward the development of a control which would pressurize the shaft and meet operational requirements.

Problems Pertinent to a Control

The use of a control at the base of the shaft to keep the inlet submerged imposed several requirements. The control must have sufficient capacity to handle the design discharge, it must be free of cavitation under all conditions of operation, it must be supported to withstand unbalanced pressures in both the vertical and horizontal directions, it must be free of any instability which might induce surging, it must be provided with controls which would keep the proper relationship of reservoir water surface to shaft water surface to prevent air entrainment, and it should be mechanically as well as hydraulically adequate. Several separate model studies were made to determine whether or not these design requirements could be met.

Description of cylinder gate model. A cylinder gate located in the bottom of the shaft at the junction of the shaft and tunnel seemed the most feasible means of controlling the flow and reservoir elevations to maintain optimum conditions. This design had the disadvantage that unwatering of the entire tunnel would be required in making inspections and repairs. However, its merits were believed to outweight this disadvantage, particularly if the gate design was hydraulically sound. Accordingly, an intensive test program was begun to develop this design. A 1:18 scale model of a preliminary design consisted of a 12-inch-inside-diameter pipe representing the 18-foot-diameter shaft, a cylinder gate of brass, a transparent plastic gate chamber to facilitate flow observations, and a 6-foot-long tunnel section of 14-inch-inside-diameter pipe (Figures 14 and 15). The 14-inch pipe was connected by a 3-foot-long reducer to a length of 12-inch pipe containing a valve for controlling the back pressure on the model.

Initial testing of cylinder gate. The model was operated according to computed head differentials based on the losses from the shaft inlet to the cylinder gate and the losses from the cylinder gate to Adaminaby Reservoir. With increasing discharge, the tunnel back pressure increases and the shaft pressure decreases such that the tunnel becomes the discharge control at about 9,000 cfs (Figure 16). Using the difference between the maximum normal head available at the shaft inlet and the computed back pressure, gate openings were determined for discharges to 9,000 cfs. The gate opening for a particular discharge was determined by adjusting the model to obtain the computed differential head. The differential head was referred to a constant tunnel back pressure of 3.3 feet (model) which submerged the gate but which did not overstress the plastic gate chamber.

Preliminary tests and observations of the gate model disclosed no adverse flow conditions that would require major changes to the design.

Pressures within the gate structure, measured with open tube water and mercury manometers, were above atmospheric with the exception of an 18-foot subatmospheric pressure on the gate seat. Pressure fluctuations were evident in the gate chamber as the jet energy was dissipated, but no movement of the model gate was discerned in the preliminary tests when the gate was suspended on three 1/4-inch stainless steel rods 18.5 inches long. These conditions were explored further in the final gate design.

Gate chamber design. Water from the junction shaft passes radially between six vanes of the gate into the gate chamber and flows (downstream) toward the Adaminaby Storage Reservoir (Figure 2). The preliminary gate chamber transition toward Adaminaby Reservoir had been tapered in plan view to converge at a 10° angle in the direction of flow (Figure 15). It was designed to aid in directing the flow from the gate to the tunnel with a minimum of head loss. The flow of water through the tunnel in one direction caused an unbalance of hydraulic pressure on the gate. This unbalance depends on the losses and flow conditions within the gate chamber and tunnel transition. A test was made on the preliminary gate and this transition to determine the effect of the transition shape on the pressure and flow conditions and to determine whether or not the unbalanced pressure would be excessive for the gate guides. Pressures were measured by piezometers at six points on the gate, one each upstream and downstream at elevations 2 feet, 6.88 feet, and 11.38 feet above the gate lip (Figure 17).

A pressure unbalance, measured at the top piezometers, varied from a maximum of 1 foot of water in the upstream direction at 2,500 cfs to a maximum of 2 feet of water in the downstream direction at 9,000 cfs. The unbalanced pressure at the middle piezometers varied from a maximum upstream of 1.8 feet at 5,000 cfs to approximately 0 at 9,000 cfs. The unbalance at the bottom piezometers was a maximum of 1.5 feet upstream at 7,000 cfs and varied to 0 at 9,000 cfs. These pressure differences were allowable since the change from a pressure upstream to a pressure downstream occured gradually.

The need for the 10° convergent transition was investigated because, structurally, the 23-foot radius reversed curve transition of the Tumut side of the initial gate chamber offered greater strength at a lower construction cost. Since there would be no flow in the tunnel upstream from the gate, the model gate chamber was tested in a reversed position.

With this arrangement, the maximum pressure unbalance in the upstream direction was 3 feet and the maximum downstream 7.2 feet. The direction of the unbalance changed with discharge but the maximum recorded in either test was 7.20 feet. This value was permissible and a gate chamber of two 21-foot-high transitions with their semicircular walls aligned on 23-foot-radius reverse curves was accepted for a final design (Figure 2).

Unbalanced horizontal forces on cylinder gate. When the transition shape had been determined and a satisfactory cylinder gate design developed, the unbalanced pressures were again measured to determine the adequacy of the gate guides. It was neither feasible nor necessary to alter the model gate height to represent the shorter final design gate. The piezometers used to measure the unbalanced pressure at the top of the gate were therefore 2.3 feet higher in the gate recess. The pressures measured by these piezometers were considered applicable because in both designs the top of the gate was within the gate recess above the crown of the gate chamber. The pressure unbalance for the recommended design was always in a downstream direction, reaching a maximum of approximately 10 feet of water at 9,000 cfs. This pressure head applied uniformly to the projected gate area would not overstress the guides and thus the designs of the gate chamber reverse-curve transition and general overall cylinder gate were acceptable.

Unbalanced vertical forces on cylinder gate. The suspension of the gate on lift stems approximately 330 feet long introduced the problem of vertical movement of the gate. A vertical movement of the gate would not result from pressure fluctuations on the top and bottom if they were in phase and equal in magnitude and occurred simultaneously around the gate. Movement could result if the fluctuations occurred simultaneously around the gate in phase but unequal in magnitude, or out of phase and equal in magnitude. To determine the tendency toward vertical oscillation and probable downpull forces, the pressure fluctuation and unbalance on the top and bottom of the gate were investigated. Water manometers were used to obtain the average pressure differences in only one section of the gate between adjacent splitters at three positions in the section (Figure 18).

From these curves, it was apparent that a change of loading would occur on the gate lift stems and hoists. Unless the loading change occurred suddenly, no movement of the gate would be expected because of the small pressure differentials. Since the inertia of water in open manometers tends to dampen pressure surges, reactance-type pressure cells were attached to Piezometers No. 1, 13, 18, and 9 to measure magnitude, frequency and phase relationships of the pressure fluctuations on the gate.

Oscillograms of the pressure fluctuations for 1,000 cfs increments of discharge were obtained with the model attached directly to the laboratory supply system. Pressure fluctuations at the gate top and bottom were essentially in phase but different in magnitude. The maximum difference of 11.0 feet occurred between Piezometers No. 13 and 1 for discharges of 7,000 and 8,000 cfs. Pressure differences were not consistently upward or downward but occurred at random at the two piezometer locations with frequencies varying between 2.5 and 5 cycles per second.

Surging was known to be present in the laboratory supply lines, and to exclude the influence of the piping system, the model was connected to an available head tank with a free water surface. In this setting, water flowed from the 6-foot-diameter head tank through a bell-mouthed entrance into the 12-inch pipe representing the 18-foot-diameter inlet shaft.

Oscillograms of pressure fluctuations were obtained for discharges of 2,000, 4,000, and 6,000 cfs, the discharge limit for the head tank arrangement. Although the peak to peak average of the pressure fluctuations was reduced by approximately 50 percent, a maximum differential of 11.0 feet was obtained for a discharge of 6,000 cfs. The frequency of pressure fluctuations had increased slightly with those at Piezometers No. 1, 13, and 18 essentially in phase between 4 and 5 cycles per second. Fluctuations at Piezometer No. 9 were about 7 per second. Because it was infeasible to attain similarity of the physical properties of the prototype and model gate structures, the effect of the pressure fluctuations and their frequency on the gate movement could be only qualitatively evaluated.

The short stems of the model (Figure 14) restrained the gate and did not provide the freedom of movement that would occur on the prototype gate. To demonstrate the possibility of a prototype gate movement, the model gate was suspended on springs to represent more nearly the long unrestrained prototype stems. The springs for the suspension of the model gate had a natural period of approximately 5 cycles per second to correspond approximately with the frequency of the pressure fluctuations. It was assumed for the purpose of testing, that if the pressure forces were large enough, the gate could move at the frequency of the pressure changes.

The model gate moved up and down under the influence of the pressure changes within the gate chamber. The movement was not regular or at a frequency of the pressure fluctuation but was at a random and lower frequency. Nevertheless, the possibility of a prototype movement was demonstrated, provided (1) the natural period of the prototype gate was near the frequency of prototype pressure fluctuations, and (2) this gate had sufficient freedom of movement to react readily to the pressure changes. Tests showed that a slight friction applied to the model gate stems would damp the movement of the gate. Friction at the guides of the prototype gate is expected to provide ample damping.

Capacity of cylinder gate. It was important that the shaft system have adequate capacity for the 9,000 cfs design discharge, therefore, a calibration was made of the model of the preliminary gate design. This calibration indicated the capacity to be more than adequate. Discharge coefficients, computed from model data, reached a maximum of 0.90 at an 8.5-foot gate opening and decreased to approximately 0.73 at a 10.8-foot maximum opening (Curve a, Figure 19). The decrease in the coefficient over the range of opening from 8.5 to 10.8 feet indicated that a loss in capacity would result by opening the gate beyond 8.5 feet. It was believed that the gate height could be reduced provided the cause of the reduction in coefficient could be determined.

At the bottom of the lower gate frame of the preliminary design there was an abrupt offset from the inside diameter of the shaft to the inside diameter of the gate. It was reasoned that as the bottom edge of the gate approached the offset, the flow pattern and the contraction changed to decrease the discharge coefficient. This was indicated by the behavior of the pressures on the bottom surface of the lower gate frame. When referred to the same datum, these pressures were higher than those on the top of the gate for gate openings up to 7 feet, equal to those at the 7-foot opening, 5 feet less at an 8-1/2-foot opening, and again equal to those at a 10-foot opening.

The lower frame of the model gate was extended downward the equivalent of 2.3 feet to ascertain if the coefficient curve was characteristic of the abrupt offset. The coefficient curve for this arrangement was of the same general shape but with the maximum discharge coefficient of 0.83 occurring at an opening of about 6.75 (Curve b, Figure 19). This test confirmed that the offset and its position with respect to the bottom of the gate were the main factors contributing to the shape of the coefficient curve. A gate shortened by 2.3 feet having a lower initial cost could be used provided the effect of the offset could be sufficiently reduced.

A gradual expansion from the inside diameter of the shaft to the inside diameter of the gate would be desirable because it would prevent the inner edge of the lower frame from influencing the contraction under the gate, give maximum capacity at full gate opening, and make the gate height a minimum. Structural limitations prevented the use of such an expansion, and a compromise was necessary.

A limited expansion of the final flow passage in the lower gate frame section of the model represented a change in diameter from 18 feet to 18 feet 11 inches in 4 feet (Figure 20). This expansion was the maximum which could be included and still provide a stiffener ring of sufficient size to support the gate frame and seal ring.

The maximum coefficient of discharge of approximately 0.83 for this arrangement was obtained at the design maximum gate opening of 7.5 feet (Figure 21). A further expansion of the lower gate frame passage would probably have increased the coefficient of discharge between the 6- and 7.5-foot gate openings. However, the gate capacity was adequate and a maximum at full opening.

Pressures at the bottom of lower gate frame were positive and slightly lower than the shaft pressure. This reduction in pressure occurred as the flow expanded to fill the passage inside the gate. The expansion of flow and the reduction in pressure was gradual and did not cause a decrease in the gate capacity at the larger openings. Apparently the inner edge of the bottom surface of the lower frame did not influence the contraction under the gate. Operating curves for the recommended design model and the pressures at the offset between the lower frame and gate are shown on Figure 22. The expansion of the lower frame from 18 feet to 18 feet 11 inches in diameter was satisfactory.

The completion of this phase of testing established the adequacy of the shaft design and all subsequent testing was focused on the hydraulic characteristics of various parts of the cylinder gate. Extensive tests were made on the gate seat and the seal at the top of the gate (Figure 20) to obtain a cavitation-free design. These tests were considered too extensive to be contained in this paper and reference is made to them only to point out the importance of considering what in many cases appears to be only minor details.

ACKNOWLEDGMENT

The series of studies discussed in this paper was made over a period of several months which enabled several Australian engineers to take part in the work. Angus McKinnon helped in the planning and testing during the early part of the program and Milton Chappel took part in later tests and analyses. Don Campbell and other Australian engineers and officials observed many of the model tests and discussed the results. Permission to use the results of the hydraulic studies discussed in this paper was granted by the Snowy Mountains Hydro-Electric Authority.

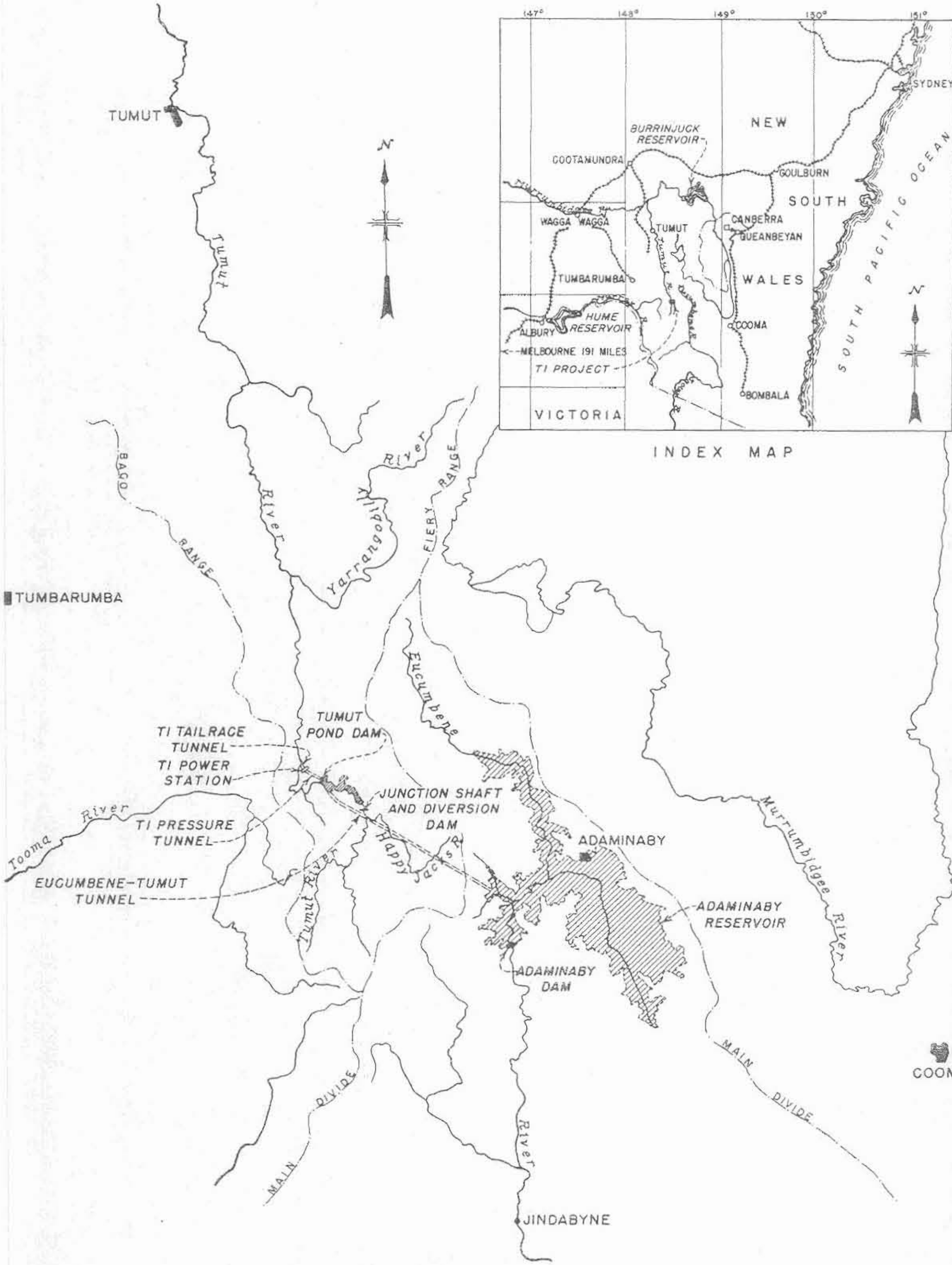


FIGURE 1 – LOCATION MAP
EUCUMBENE-TUMUT TUNNEL–T-1 PROJECT, AUSTRALIA

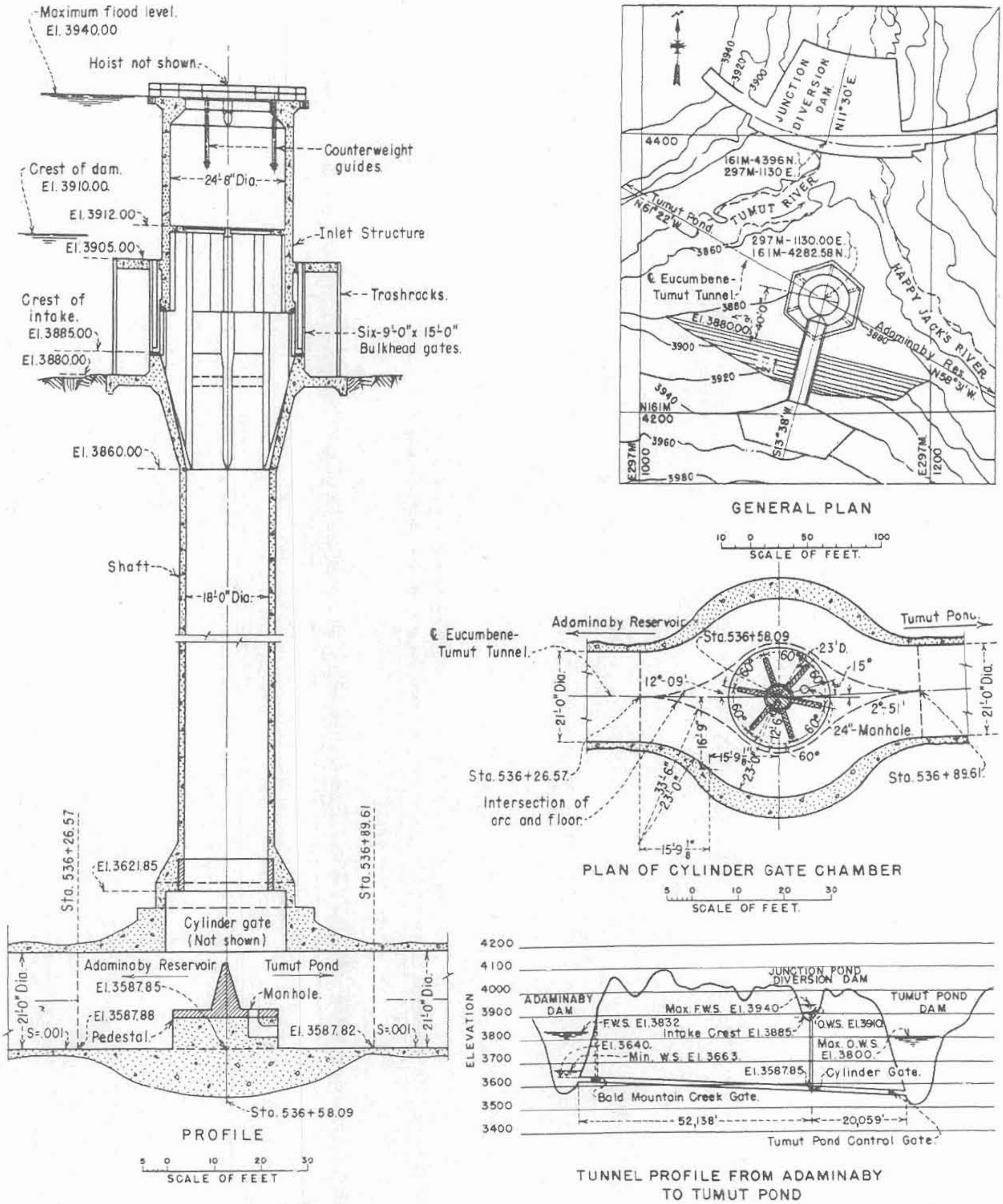


FIGURE 2– EUCUMBENE-TUMUT TUNNEL INTAKE SHAFT

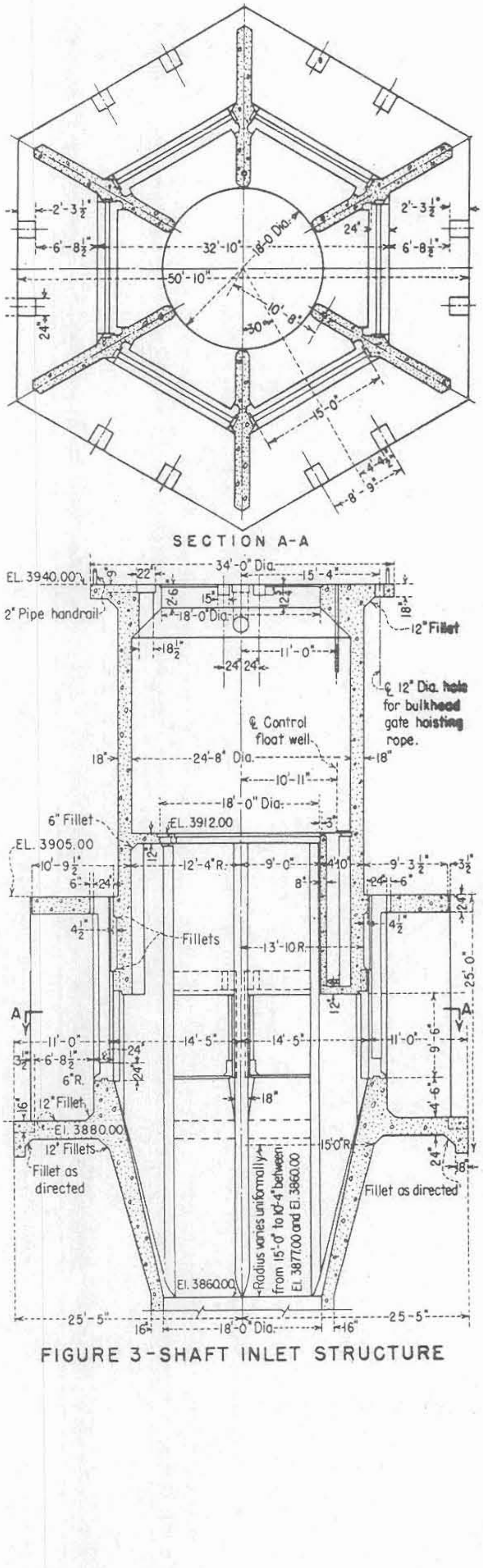


FIGURE 3-SHAFT INLET STRUCTURE

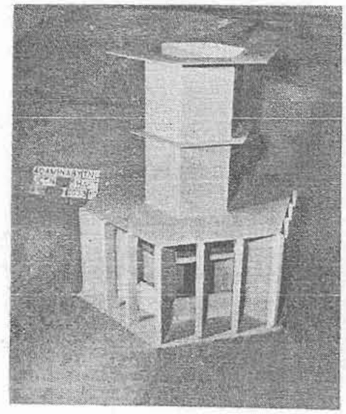


FIGURE 4-1:21.6 SCALE MODEL SHAFT INTAKE

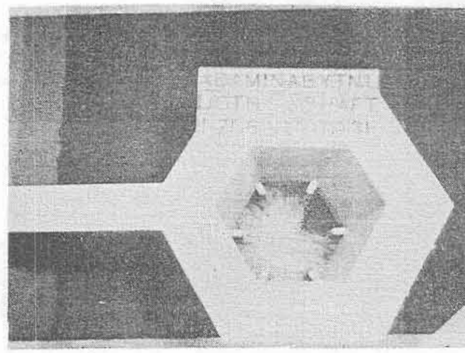


FIGURE 5-WATER SURFACE WITHIN MODEL SHAFT INLET

FIGURE 6-FREE FLOW OVER INLET CREST 9000 C.F.S.

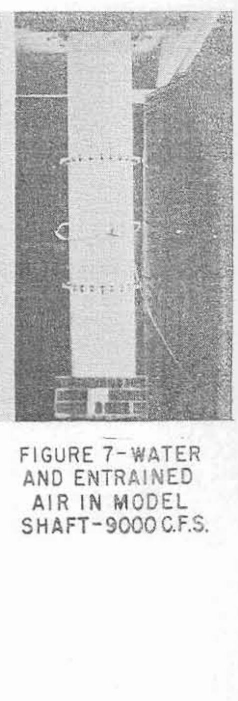


FIGURE 7-WATER AND ENTRAINED AIR IN MODEL SHAFT-9000 C.F.S.

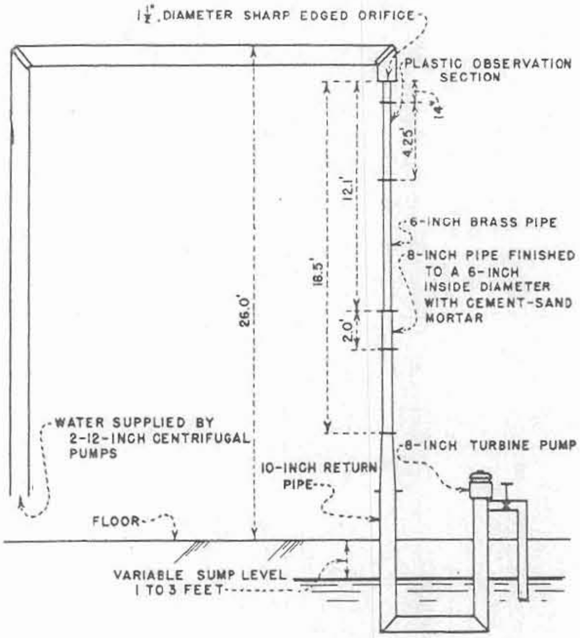


FIGURE 8-MODEL REPRESENTING CONTROL AT SHAFT INLET

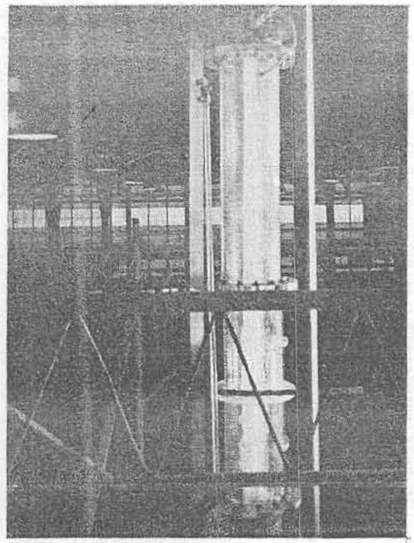
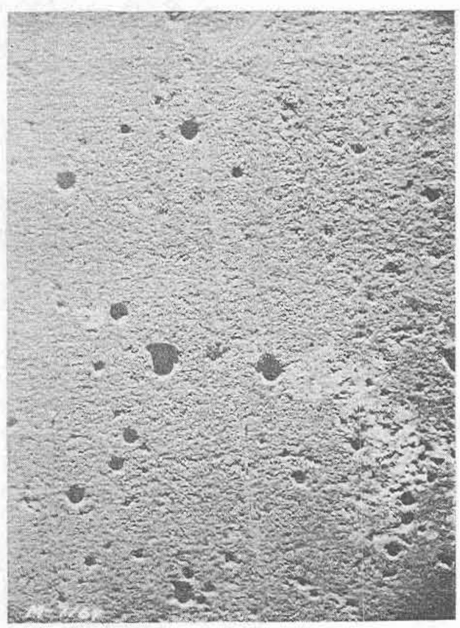


FIGURE 9-TURBULENT SURFACE ERUPTION, HIGH-VELOCITY JET IN 6-INCH PIPE

A-SURFACE AFTER 25 HOURS



B-SURFACE AFTER 100 HOURS

FIGURE 10-CONCRETE PIPE SUBJECTED TO CAVITATION

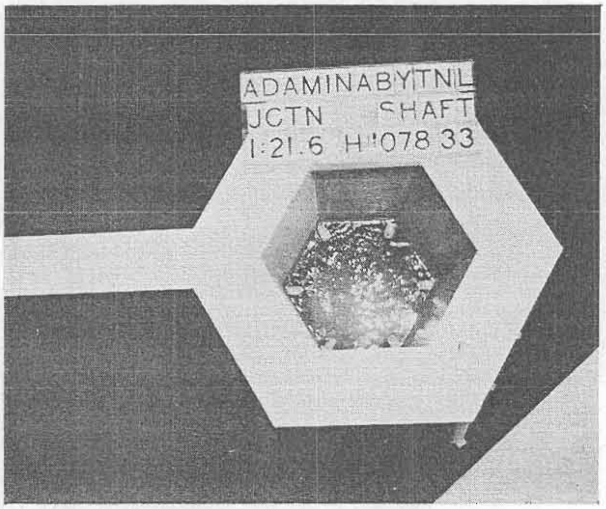


FIGURE 11-WATER SURFACE IN SHAFT

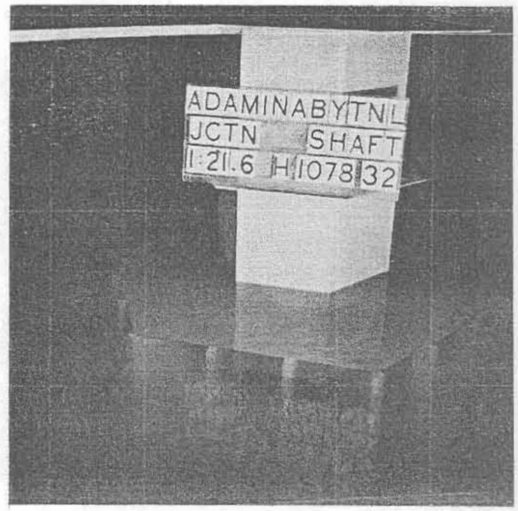


FIGURE 12-FLOW CONDITIONS
SHAFT INLET SUBMERGED

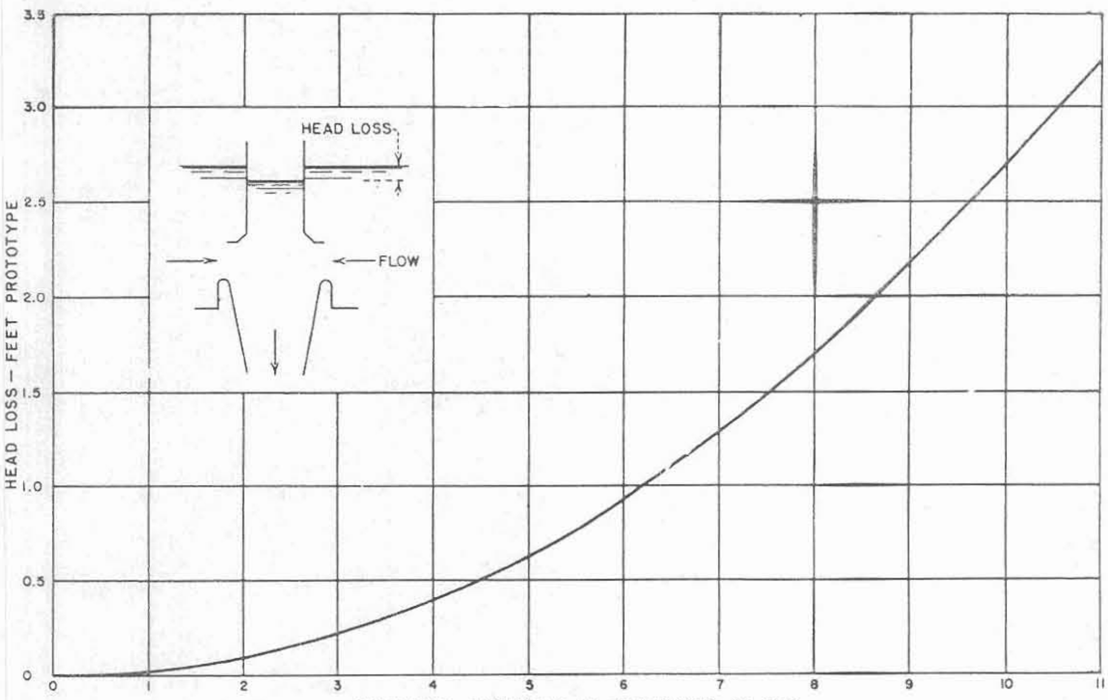


FIGURE 13-HEAD LOSS-SHAFT INLET

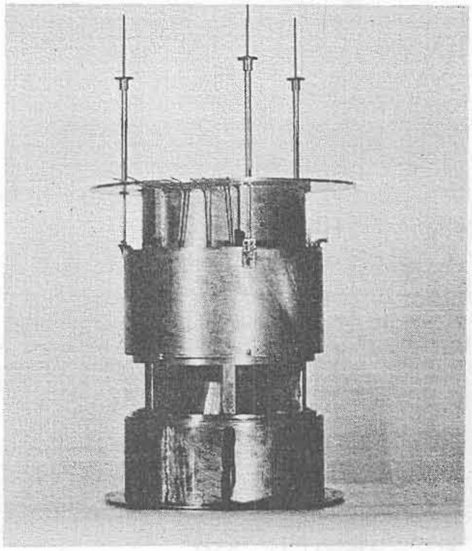


FIGURE 14 — ASSEMBLED 1:18 SCALE MODEL OF CYLINDER GATE

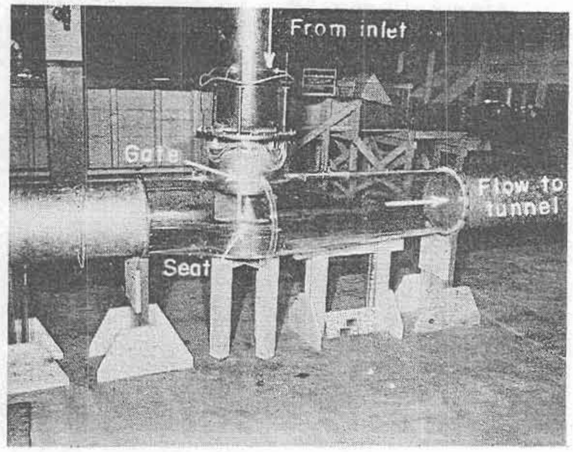


FIGURE 15 — 1:18 SCALE MODEL OF CYLINDER GATE AND TUNNEL TRANSITIONS

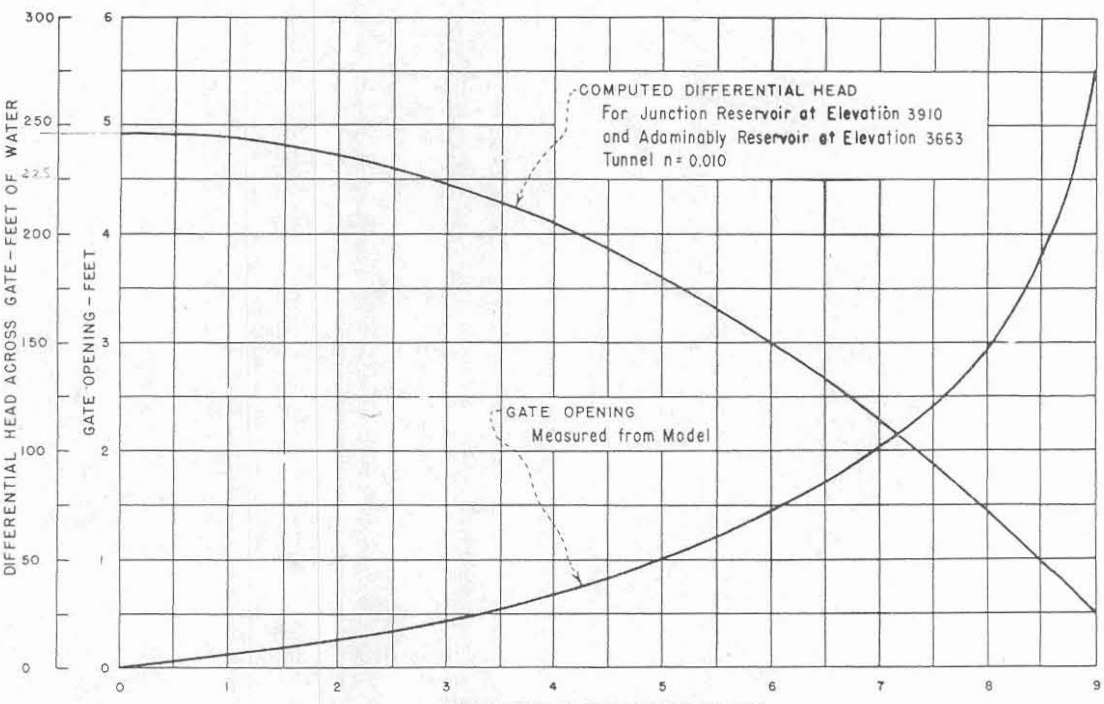


FIGURE 16 — HYDRAULIC CHARACTERISTICS OF TUNNEL SHAFT INTAKE

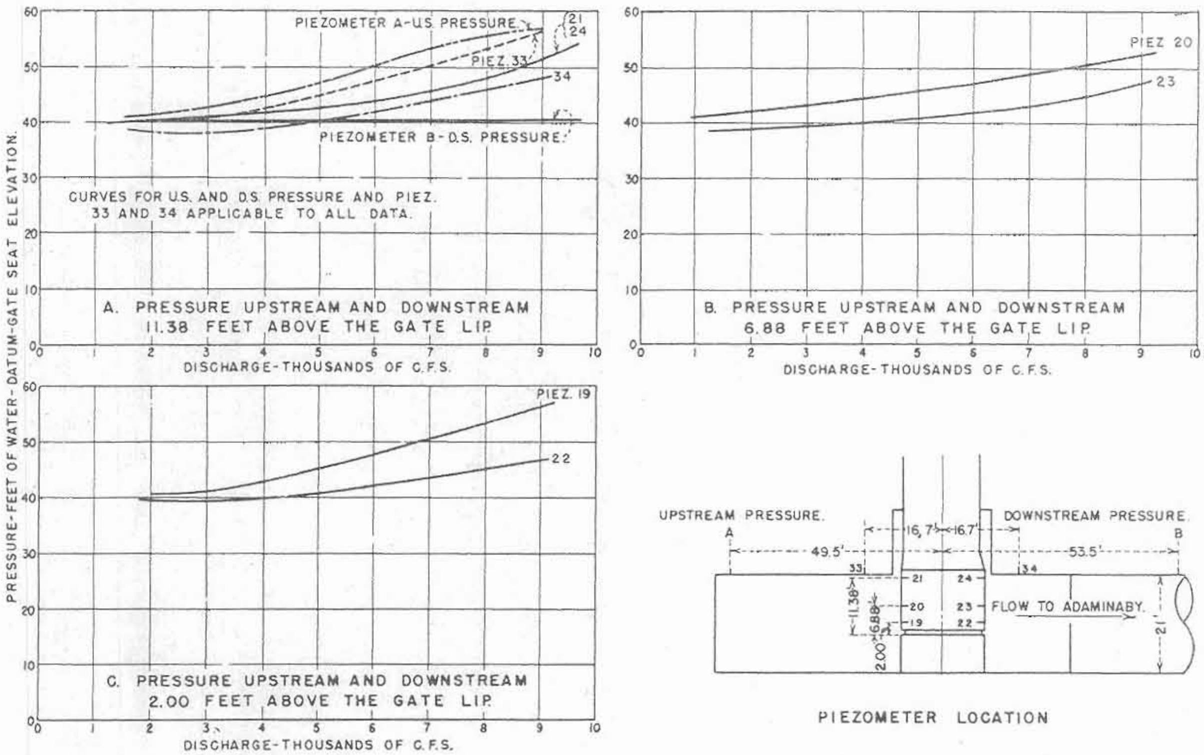


FIGURE 17 - UNBALANCED HORIZONTAL PRESSURES ON CYLINDER GATE

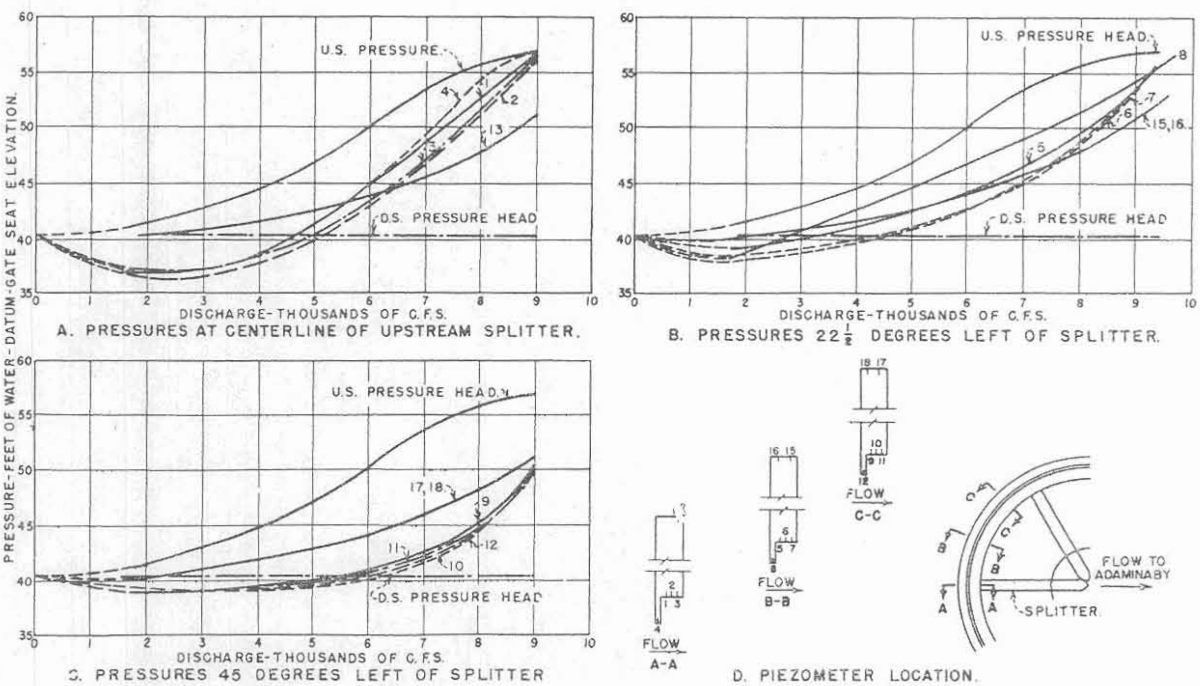


FIGURE 18 - UNBALANCED VERTICAL PRESSURES ON CYLINDER GATE

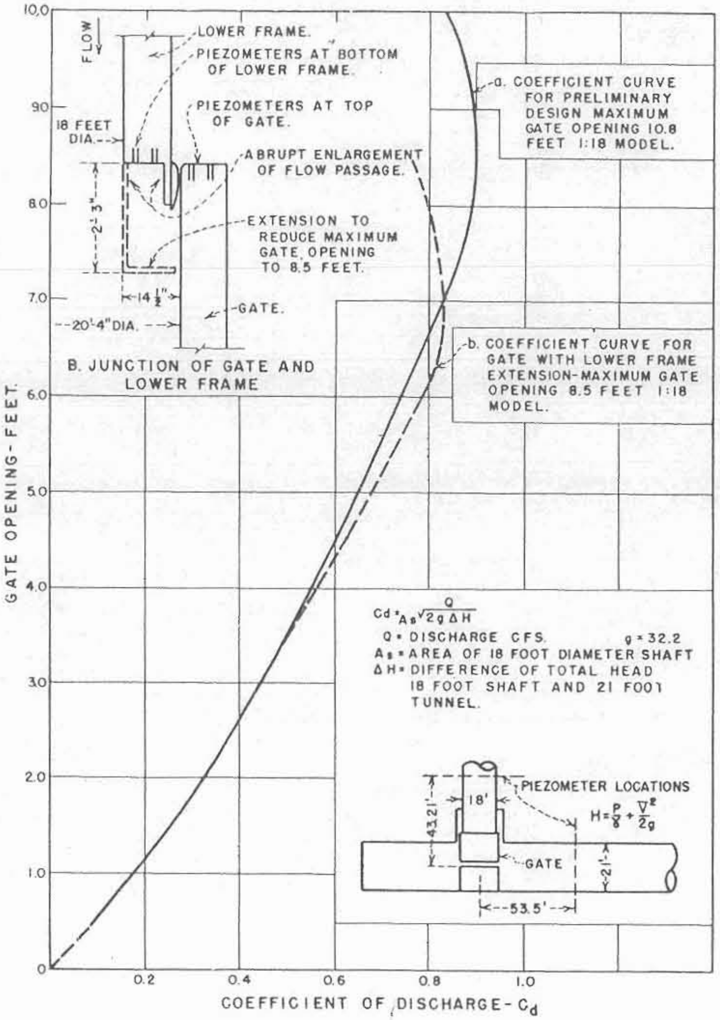


FIGURE 19-DISCHARGE COEFFICIENTS PRELIMINARY DESIGN CYLINDER GATE WITH 10.8 AND 8.5 FOOT MAXIMUM OPENINGS

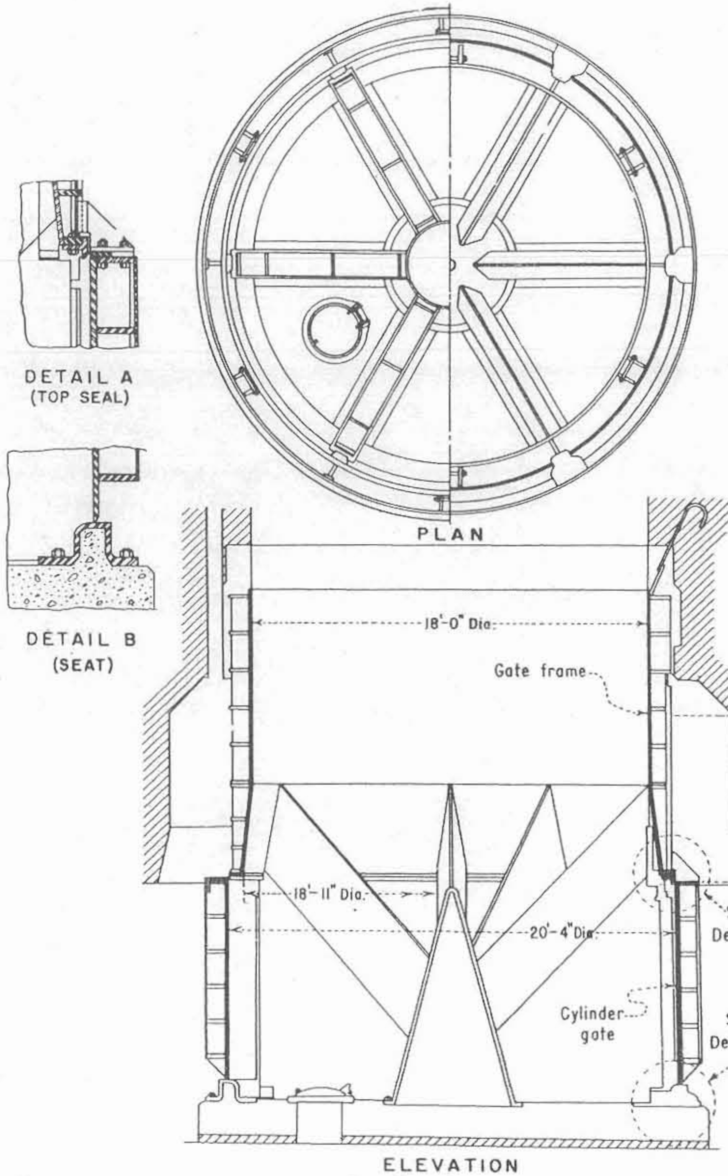


FIGURE 20-CYLINDER GATE AND FRAME

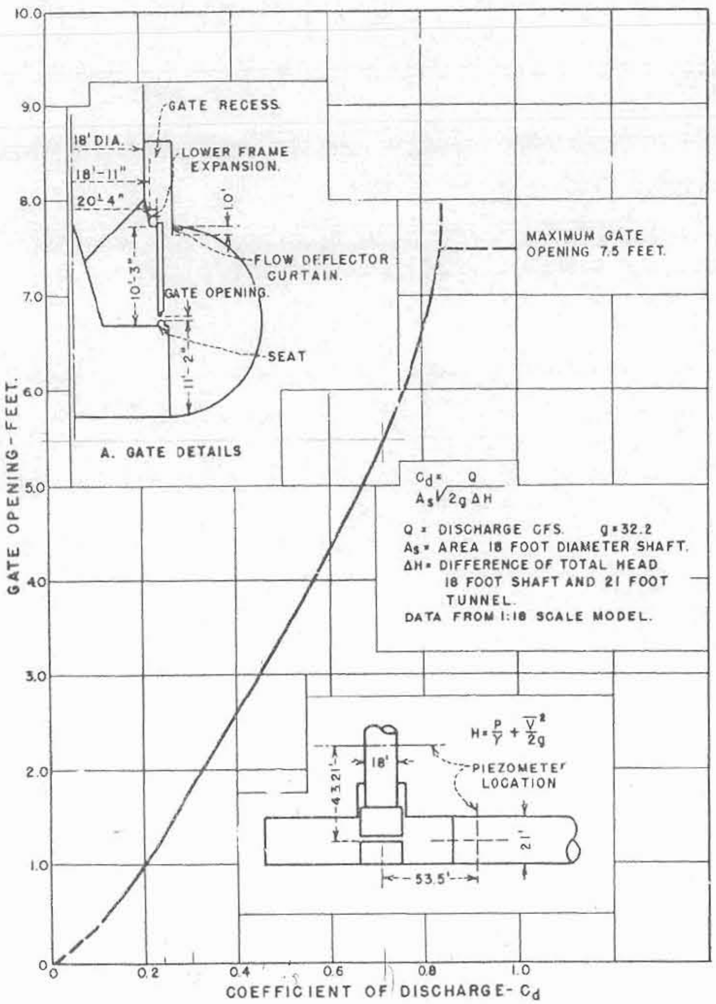


FIGURE 21-DISCHARGE COEFFICIENTS FOR RECOMMENDED CYLINDER GATE

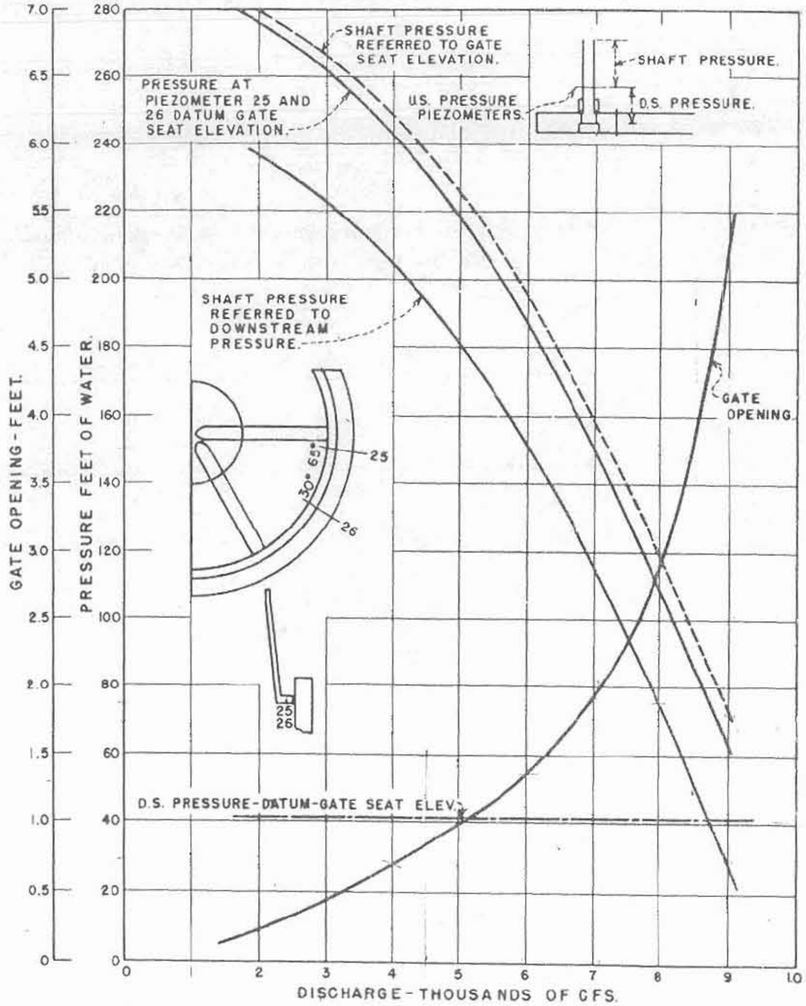


FIGURE 22-CYLINDER GATE DISCHARGE CHARACTERISTICS AND GATE FRAME PRESSURES

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